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Infrared Physics & Technology 36 (1995) 1025–1034

INFRARED PHYSICS
& TECHNOLOGY

Search strategy for optimal infrared target acquisition performance

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Received 6 January 1995

Abstract

The search strategy in field-of-regard infrared target acquisition is considered. Three methods of choosing the sequence of fields-of-view to be searched in the field-of-regard are considered: random, 'windshield-wiper' and 'typewriter'. The effect of the speed of the scan on the blurring of the target image is considered. The results are used to predict the performance of actual military systems.

1. Introduction

In the military environment, two forms of search are used when infrared target acquisition is performed using electro-optic equipment. Field-of-view search consists of a human visually searching a fixed screen, attempting to acquire a target; field-of-regard search involves the changing of the field-of-view (either continuously or at discrete times) while searching for the target. This second type of search is the most common in practical military scenarios and must be properly modeled to correctly evaluate the effectiveness of electro-optical scanning military hardware.

The standard military model for infrared target detection is the Night Vision and Electronic Sensors Directorate (NVESD) target acquisition model [1]. This model of thermal image performance

relates the sensitivity and resolution of the sensor, the thermal contrast of the target to the background, and the transmission of the atmosphere to the probability of detection, recognition, and identification. The model was designed to give a value of the static probability of detection without search. It has been modified for the time-dependent probability of detection (where the target is at an unknown position and, hence, acquisition involves both the search and detection processes) [2–6].

In this paper we wish to extend the model to field-of-regard search, in which a variety of possible methods of search are considered. In addition, the speed of the sensor, if we consider it to be moving smoothly within the field-of-regard, will affect the observed image quality. We will take this blurring into account to consider the optimum search strategy.

The model accepts as given the single glimpse detection probability when the target is in the field-of-view. Section 2 discusses how to derive the value of this parameter as a function of the other parameters of the electro-optical system. Section 3 describes three types of search and the effect that each method has on the rate of target acquisition. Section 4 then considers how to vary the single glimpse probability to account for the natural blurring that occurs due to the sensor motion. Section 5 relates these results to those of several common FLIRS (Forward Looking Infrared Sensors) to permit determination of the optimum search strategy. The results are then used to compute the performance of actual military systems.

2. Thermal image performance model

A function often used to characterize FLIR performance is the minimum resolvable temperature (MRT) [7]. MRT is the smallest change in blackbody equivalent temperature that can be detected clearly by the thermal imaging system. MRT is a function of spatial frequency since smaller target images require larger temperature differences in order to be observed. Therefore, MRT increases with spatial frequency. Assume, as done in Ref. [3], that the MRT dependence on the spatial frequency ν (in cycles/rad) is given by

$$\text{MRT} = \text{MRT}_0 \exp(\beta_{\text{sys}}^{\nu}), \quad (1)$$

where MRT_0 is the limiting MRT as ν approaches 0 and β_{sys} is the system coefficient. We can find ν from the target characteristics by

$$\nu = \frac{\gamma}{s} R, \quad (2)$$

where R is the range in meters, s is the minor dimension of the target in meters, and γ is the task difficulty function (1 for detection and 4 for recognition).

The ratio of the atmospherically degraded target-background thermal contrast to the aspect-corrected value of the MRT is called the normalized signal-to-noise ratio. The atmospherically degraded thermal contrast at high-resolution-limiting spatial frequencies is approximated by $\Delta T\tau$,

where ΔT is the temperature difference between a target and its background assuming no path radiance; τ , the transmission, is given by

$$\tau = \exp(-\beta_{\text{atm}} R), \quad (3)$$

where R is the range as used in Eq. (2) and β_{atm} is the extinction coefficient of the atmosphere. The MRT must be normalized by a factor $(\epsilon/7)^{1/2}$, where ϵ is the ratio of the long to short dimensions of one equivalent target line of the target, to account for targets that are not square in shape. The signal-to-noise ratio (SNR) is defined as [7]

$$\begin{aligned} \text{SNR} &\equiv \frac{\Delta T\tau}{\text{MRT}/(\epsilon/7)^{1/2}} \\ &= \frac{\Delta T \exp(-\beta_{\text{atm}} R)}{\text{MRT}_0 \exp(\gamma\beta_{\text{sys}} R/s)/(\epsilon/7)^{1/2}}. \end{aligned} \quad (4)$$

The condition $\text{SNR} = 1$ corresponds to a 50% static detection probability. Thus, for this case the range at 50% labeled $R(0.5)$ equals

$$R(0.5) = \frac{\ln[\Delta T(\epsilon/7)^{1/2}/\text{MRT}_0]}{\beta_{\text{atm}} + (\gamma/s)\beta_{\text{sys}}}. \quad (5)$$

The model provides a method for the calculation of ranges for a static detection probability other than 50%. This is done by incorporating a factor K_ρ into our equation. The relation between ρ and the ranges $R(\rho)$ at which the probability of detection ρ is other than 0.5 is given by

$$R(\rho) = \frac{\ln[\Delta T(\epsilon/7)^{1/2}/\text{MRT}_0]}{\beta_{\text{atm}} + K_\rho(\gamma/s)\beta_{\text{sys}}}, \quad (6)$$

where K_ρ can be approximated by a formulation proposed by Kornfeld [8]

$$\rho = \frac{K_\rho^E}{1 + K_\rho^E}, \quad (7)$$

and E equals

$$E = 2.7 + 0.7K_\rho. \quad (8)$$

This assumes that for a particular value of K_ρ

$$\nu = \frac{\gamma}{s} RK_\rho. \quad (9)$$

It approximates performance in conditions such as relatively good weather where the limitation on performance is primarily due to sensor resolution.

Thus, we can determine the value of the range for any desired probability of detection if the actual position of the target is known. We note that ρ here is the static probability of detection at infinite time when the position of the target is known.

By inverting Eq. (6), we find

$$K_p = \frac{\ln \left[\frac{\Delta T \sqrt{\epsilon/7}}{MRT_0} \right] - R\beta_{\text{atm}}}{\gamma\beta_{\text{sys}} R/s}. \quad (10)$$

This, with Eqs. (7) and (8), gives the probability of detection for a given range.

To estimate timeline performance incorporating human search, the CNVEO proposed a search model based on a process by which every target is characterized by a probability of detection at infinite time P_∞ and a single-glimpse probability of detection P_0 for that fraction of the normal observer ensemble that can detect the target [4,5]. The approximation that all observers who can acquire the target do it at a constant rate is maintained here for consistency with the traditional CNVEO search model. In that case, the probability of detection $P(t)$ is

$$\begin{aligned} P(t) &= P_\infty \left[1 - \exp\left(-\frac{t}{\tau_{\text{au}}}\right) \right] \\ &= P_\infty \left[1 - \exp\left(-\frac{P_0 t}{t_f}\right) \right], \end{aligned} \quad (11)$$

where $t_f \approx 0.3$ s is the time to take a single glimpse and $\tau_{\text{au}} = t_f/P_0$ is the mean acquisition time. For small P_0 and P_∞ , P_0/t_f has been empirically found to equal $P_\infty/3.4$ and hence

$$P(t) = P_\infty \left[1 - \exp\left(-\frac{P_\infty t}{3.4}\right) \right]. \quad (12)$$

The term P_∞ in the search model is given by the value of ρ ; ρ can be derived from Eqs. (10), (7) and (8) [4,5]. To incorporate clutter, K_p is replaced in Eqs. (7), (8) and (10) with K_p/CF ; CF is an empirical factor to include the effect of clutter. As the degree of clutter changes, thereby changing the search process, the value of P_∞ changes [4]. The term P_∞ represents the fraction of the normal observer ensemble that can successfully find the target in infinite time.

3. Field-of-regard search

3.1. Basic assumptions

We must clearly define our assumptions to describe the field-of-regard scenario. We assume that we have N fields-of-view in the field-of-regard. These fields of view are sequential in the horizontal dimension; in the vertical dimension, the field-of-regard is contained in the vertical field-of-view of the sensor, i.e. linear search is the type of search considered in this paper. Once one starts observing a field-of-view, it is in the sensor's field-of-view for T seconds. The fields-of-view are viewed separately, i.e. rather than panning a scene smoothly going from one field-of-view to the next, one rather jumps from a field-of-view to another field-of-view. While this is not the natural way of search, it simplifies the math without grossly distorting the conclusion. We will convert our model to one for a continuous smooth search in Section 3.5.

It takes no time to jump from one field of view to another. The target is equally likely to be in any field-of-view. We assume that the target acquisition process, when the target is in the field of view, is a Poisson process. If the target is in the field-of-view, the probability of acquiring the target in the next Δt seconds is $(P_0/t_f) \Delta t$ for small Δt where P_0 is the single glimpse probability and t_f is the time for a single glimpse. The probability of finding the target while it is present for the T seconds the viewer is observing it equals p , where

$$p = 1 - \exp(-P_0 T/t_f). \quad (13)$$

Given the target is found in a particular viewing of a field-of-view, the expected value of the time T_0 spent in that field-of-view to find it is: [6]

$$\begin{aligned} T_0 &= \int_0^T (P_0 t/t_f) \\ &\quad \times \exp(-P_0 t/t_f) dt / [1 - \exp(-P_0 T/t_f)]. \end{aligned} \quad (14)$$

If T_0 is small relative to the amount of time generally spent on search, a calculation of the probability of detection is equivalent to a calculation of the number of screens searched until the 'successful' screen is reached (with the subsequent detection). This is the approach used here.

For the following definitions, let us assume that the five field-of-views, sequentially labeled from left to right 1, 2, 3, 4 and 5. (We note that, in the analysis that follows these definitions, we do not rely on this – the number of fields-of-view can be set in the model!)

We will define three types of search:

(1) *Random search*: The field-of-view to be next observed is chosen randomly, independent of the present field-of-view. Thus, one possible field-of-view search pattern is

2 4 5 1 3 3 2 4.

(2) *Typewriter search*: One sequentially examines the field-of-view from left-to-right. When one reaches the rightmost field-of-view, one starts again at the leftmost one. Thus, one possible search pattern is

3 4 5 1 2 3 4 5 1.

Note that the search did not have to start at 1.

(3) *Windshield wiper search*: One begins searching in one direction; when one reaches the last field-of-view, one reverses direction while starting with the field-of-view last viewed. Thus one possible pattern is:

3 4 5 5 4 3 2 1 1 2 3.

(We note that we have somewhat unnaturally doubled the first and last fields of view. We have done this because (a) there is no good reason why, after a left-right-left-sweep, the right-most field-of-view should be the only one that was not searched twice, (b) in a continuous smooth sweep there would be some points in the last field-of-view which would be scanned for as much as $2T$ (those points on the left-hand side of the right-most field of view in a left-to-right-to-left scan) and (c) it simplifies the math considerably. This does not significantly change the results.)

3.2. Search times

3.2.1. Random search

We will calculate the probability that the target has not been detected in random search after looking at L fields-of-view. There are N fields-of-

view in the field-of-regard. For a single field-of-view, the probability of not finding the target is

$$P(1) = [(N-1)/N] + [(1-p)/N], \quad (15)$$

where $(N-1)/N$ is the probability that one is looking at the wrong field-of-view while $(1-p)/N$ is the probability that one is looking at the right field, but did not find it. The probability $P(L)$ that one has not found it after L screens is

$$P(L) = \{[(N-1)/N] + [(1-p)/N]\}^L. \quad (16)$$

The probability $P^*(L)$ that one finds the target on screen $L+1$ and does not find it after L screens is

$$P^*(L) = -(\{[(N-1)/N] + [(1-p)/N]\}^{L+1} - \{[(N-1)/N] + [(1-p)/N]\}^L). \quad (17)$$

The expected value of the number of screens needed to be searched to find the target before getting to the successful screen is

$$E(L) = \sum_{L=0}^{\infty} (L)P^*(L) = \sum_{L=0}^{\infty} P(L) - 1. \quad (18)$$

For random search,

$$E(L) = N/p - 1. \quad (19)$$

3.2.2. Typewriter search

We must now consider other forms of search. Let us consider typewriter search as described in Section 3.1. Where one starts does not affect the target acquisition probabilities. Assume that

$$L = mN + r, \quad (20)$$

where L is the total number of screens searched until the screen in which the target is detected is reached, m is the integer number of times that the entire field-of-regard has been searched, and r is the remaining field-of-views that have been searched on the present $m+1$ 'st sweep. Since in the m field-of-regard sweeps we know that the field-of-view with the target was observed m times, we have the following expression for the probability of no detection after L screens ($L = mN + r$)

$$P(L) = [1-p]^m \{[(1-p)r/N] + (N-r)/N\}, \quad (21)$$

where $(1-p)^m$ is the probability the target was not found in m sweeps, $[(1-p)r/N]$ is the probability

the screen was checked one more time and the target was not found, while $[(N-r)/N]$ is the probability that the right screen was not obtained yet on the last sweep.

Once again, as in (17),

$$P^*(L) = -[P(L+1) - P(L)]. \quad (21a)$$

The expected value of the number of screens to search until the 'successful' screen is reached is

$$E(L) = (N/p) - 1 - (N-1)/2. \quad (22)$$

3.2.3. Windshield wiper search

The calculations for windshield wiper search are fairly tedious; they are complicated because they must take into account end effects. Assume that one has started on the first (left-most) field-of-view with five fields-of-view in the field-of-regard. In this case, efficient search would occur, at least for the first five fields-of-view, since the observer would proceed

1 2 3 4 5.

However, if he started on 4, the search pattern would be

4 5 5 4 3 2.

Clearly this is less efficient, looking at 4 and 5 twice and never looking at 1.

After careful accounting for all the possible starting positions, we can find the relevant probability of detection as follows. A sweep must now be defined as the completion of both a left- and right-handed sweep of the picture (i.e., the examination of $2N$ fields-of-view). Thus let us let

$$L = 2mN + r, \quad (23)$$

where r is the remaining fields-of-view after all the complete sweeps have been done. In this case, let

$$t = (r-d)/2, \quad (24)$$

where $d = 0$ if r is even, and $d = 1$ if r is odd. The probability of not finding the target by L screens can be shown to be

$$P(L) = [1-p]^{2m} \times [N^2 - (2t+d)Np + t(t+d)p^2]/N^2. \quad (25)$$

Of course, the probability of first finding it on the $L = 1$ 'st screen, $P^*(L)$, is given by Eq. (21a).

The expected value of the number of screens to be looked at before the target acquisition occurs is

$$E(L) = [N/p - 1] - [(N-1)/2] + \{[N - (1/N)]/(12 - 6p)\}. \quad (26)$$

4. Sensor motion dependent minimum resolvable temperature

We now wish to introduce a motion-dependent component into the above model. We will do this by altering the value of the extinction coefficient β_{sys} to reflect the sensor motion.

Our approach is as follows: The minimum resolvable temperature defined in (1) is inversely proportioned to the MTF of the system. Let us define an MTF_s and MTF_m which corresponds to the MTF of the stationary and moving systems respectively. There will correspondingly be an MRT_s and MRT_m for the stationary and moving systems also. MTF_m is equal to MTF_s times the MTF caused by the sensor blur, MTF_b . MTF_b has been given by [9]

$$MTF_b = \sin x/x, \quad (27)$$

where

$$x = \pi v v t_i, \quad (28)$$

and v is the spatial frequency in question (cycles per radian), v is the angular velocity of the sensor (in radians per second) and t_i is the integration time of the system in seconds.

The correct integration time to use is actually a very complicated issue. The integration time of the eye is approximately 100 milliseconds; however, experimental evidence indicates that for a moving target on a screen, much better temporal resolution can be obtained [10]. We will therefore set the time for integration to 10 milliseconds; this number is derived from the experimental observation that for slew rates greater than $10^\circ/\text{sec}$ for targets at a distance between 2–5 km, target acquisition becomes impossible [11]. (This calculation was derived for TV systems and not FLIRS; by using it

here, we assume that the same human visual limitations apply for both systems.)

Since MRT is inversely related to MTF, we can derive

$$\text{MRT}_m = \text{MRT}_s(x/\sin x). \quad (29)$$

Since MRT is exponentially related to β_{sys} (Eq. (1)), we can relate MTF_m to a new β_{sys}^*

$$\text{MRT} = \text{MRT}_0 \exp(\beta_{\text{sys}}^* v), \quad (30)$$

where (for $v < v_{\text{max}} = 1/[vt_i]$)

$$\beta_{\text{sys}}^* = \beta_{\text{sys}} + \ln(x/\sin x)/v. \quad (31)$$

The second term represents the effect of the blurring.

5. Implementation

Implementation of the model involves the following input parameters (all described above):

Target and atmosphere characteristics: ΔT , R , s , β_{atm} , ϵ , and CF,

Systems characteristics: MRT_0 and β_{sys} ,

Search strategy: γ (task difficulty), v , N , t_i , size of field of view, and the type of search (random, typewriter, windshield wiper).

The model is then implemented as follows, the spatial frequency of the target v is calculated in (2) (where for detection we are using the value γ equal to 1); x is calculated in (28). At this point the new extinction coefficient of the system is calculated in (31). The probability of detection ρ can then be calculated from (10) and (7).

The inputs to the model described in Section 3 are now ready. N and T are external inputs; P_∞ equals ρ/CF , and P_0/t_f equals $P_\infty/3.4$ (as discussed in the text preceding (12)). We have three cases: for random search, the probability of detection $P(t)$ is related to $P^*(L-1)$ (the probability the target is detected on the L 'th screen) by

$$P(t) = P_\infty P^*(L-1). \quad (32)$$

To convert this equation to the continuous case, we will replace the number of 'unsuccessful' screens L by the variable t/T . We then obtain

$$P(t) = P_\infty P^*([t/T] - 1), \quad (33)$$

where $P^*(L)$ is given in (17). For integer values of t/T , (32) and (33) are identical; for non-integer t/T , (32) is a reasonable interpolation. For typewriter search, (33) still applies, where $P^*([t/T] - 1)$ is obtained from (21) and (21a). Finally, for windshield wiper search, (33) is again used with (21a) and (25).

6. Experimental and simulation results

6.1. Comparing search strategies

We will start our analysis with the model presented in Section 3. Figs. 1–3 present the results of the model when given values for N , P_0/t_f , T and P_∞ . Several conclusions become apparent:

- (1) The typewriter method is clearly the most efficient method of search, with windshield-wiper second and random search last.
- (2) The difference in acquisition times between the three methods becomes more important as the number of fields-of-view to search increases.
- (3) The difference in acquisition times increases as P_0/t_f increases.

6.2. Comparing search speeds

In Figs. 4 and 5, we compare the effect of several scan speeds on the probability of target acquisition.

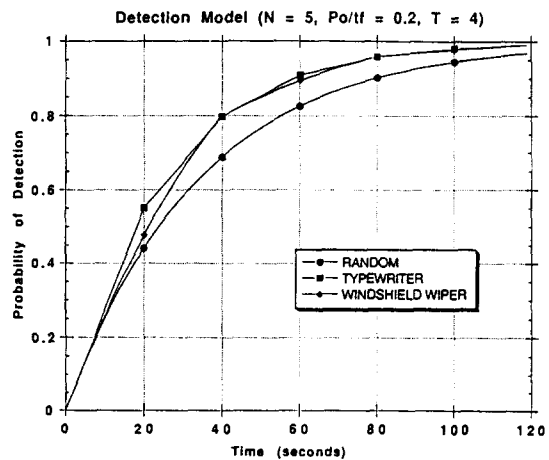


Fig. 1. Probability of detection versus time for different search strategies ($N = 5$, $P_0/t_f = 0.2$, $P_\infty = 1.0$, $T = 4$).

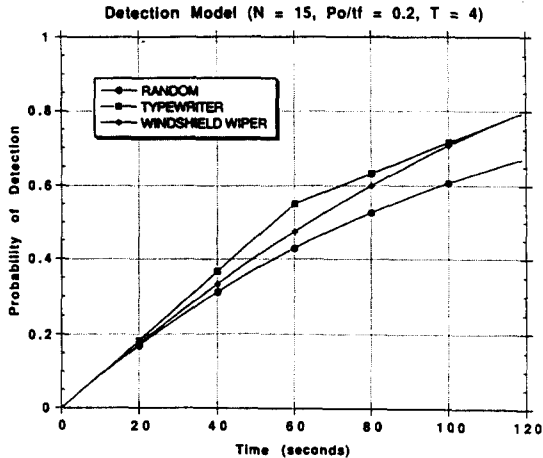


Fig. 2. Probability of detection versus time for different search strategies ($N = 15$, $P_o/t_f = 0.2$, $P_x = 1.0$, $T = 4$).

sition. We pick one characteristic sensor, the 1974 (8–12) micron FLIR as described in Ref. [6]. The details of our scenario are given in Tables 1–3. Several different speeds were chosen and two ranges, 2 km and 4 km. The results are shown in Figs. 4 and 5.

In Fig. 4, where the target is located at 2 km, an increase in sensor speed essentially results in an increase in target acquisition probability. The target is fairly obvious and the time for target detection is controlled by the time for the sensor to reach the correct field-of-view.

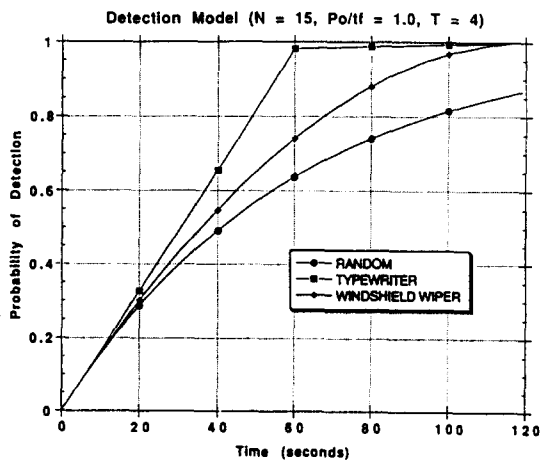


Fig. 3. Probability of detection versus time for different search strategies ($N = 15$, $P_o/t_f = 1.0$, $P_x = 1.0$, $T = 4$).

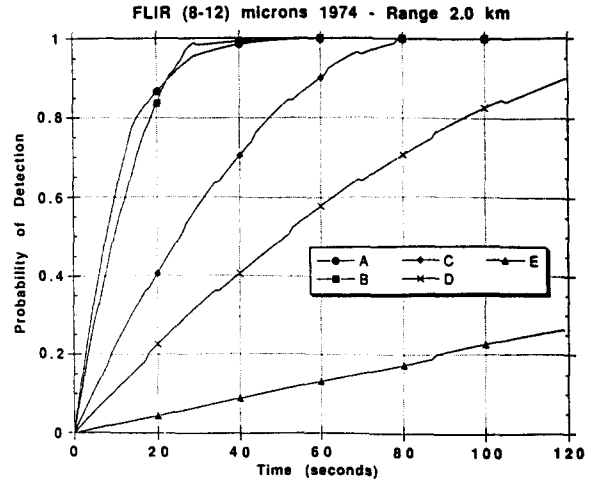


Fig. 4. Probability of detection versus time for FLIR 1974 (18–12 micron) with the range equal to 2.0 km (A – 0.06, B – 0.03, C – 0.01, D – 0.005, E – 0.001 (rad/sec)). Other parameters taken from Tables 1–3.

In Fig. 5, a different result occurs, when the target is at 4 km. Initially, once again, increasing the sensor scanning speed increases the probability of target acquisition. However, as we increase the speed even further, the probability of detection decreases. This is because the blurring of the picture causes a decrease both in the rate of acquisition and in the fraction of the observer population that can acquire the target.

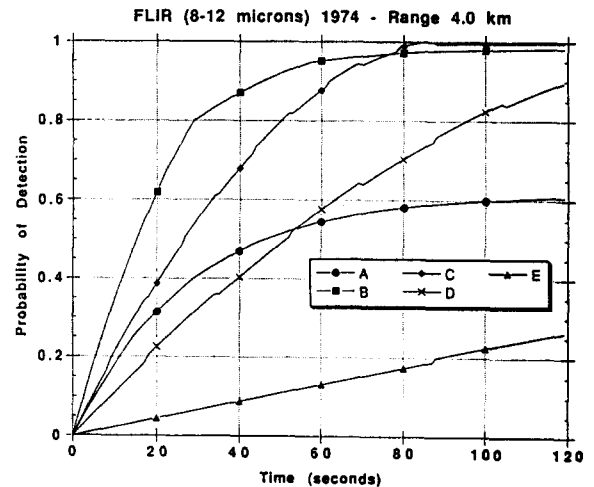


Fig. 5. Probability of detection versus time for FLIR 1974 (18–12 micron) with the range equal to 4.0 km (A – 0.06, B – 0.03, C – 0.01, D – 0.005, E – 0.001 (rad/sec)). Other parameters taken from Tables 1–3.

Table 1
Characteristics of the target

s	3 m
ϵ	2
ΔT	2°
R	2, 4 km
β_{atm}	0.15 km ⁻¹
CF	1

6.3. Smoke week 5B – Field test

In 1983, the Smoke 5B field experiment was performed at Fort Huachuca, Arizona [11]. Several different types of targets (tanks, armored personnel carrier, trucks) were presented to users using different types of electro-optical equipment to test the observers probability of detection and time for detection. The trials were search experiments, in which a broad field-of-regard was searched by sensors with limited field-of-view. The search process continued for approximately twenty minutes while targets were present for approximately eighty second stretches.

A detailed analysis of the experiment by us is impossible; what is missing, as the report indicates, is a video record of the scenery viewed through the thermal sensor while the operator searched [11]. However, in this section, we wish to see if the overall trends in the data can be explained.

Fig. 6 gives the experimentally measured probability of detection and recognition for one type of sensor (AN/TAS-4 Tow Night Sight) against all of the targets. It is immediately apparent that, as expected, the more distant targets are more difficult to detect. We wish to examine these results in light of our model.

To model this situation, we must construct a generic description of the target, sensor and search pattern. Tables 4–6 give the characteristics of the search process. The characteristics of the sensor

Table 2
Characteristics of the sensor

1974 FLIR (8–10 μm)	
MRT_0	0.0254°C
β_{sys}	0.996 mrad/cycles

Table 3
Characteristics of the search process

γ	1
Field-of-view	5°
v	0.06, 0.03, 0.01, 0.005, 0.001 rad/sec
type of search	typewriter
t_i	0.01
N	5
CF	1

and the search process are typical values found in Ref. [11]; the characteristics of the target are the generic ones given in Refs. [3] and [6]. We note that these values are generic and reasonable (especially ΔT and the clutter factor).

It is clear that the theoretical analysis derived here, when blur is not included, somewhat overestimates the target acquisition capability at long ranges; when the blurring effect is included, the model somewhat underestimates the target acquisition possibilities. We are reasonably satisfied with these results; Ref. [11] does note that some of the targets were detected at long ranges while they were moving into position. It is well-known that moving targets are considerably easier to detect. (Modeling this effect in the CNVEO model is a subject of future work.)

In Fig. 7, we use the same sensor and search scenario as in Fig. 6, except the range is fixed at

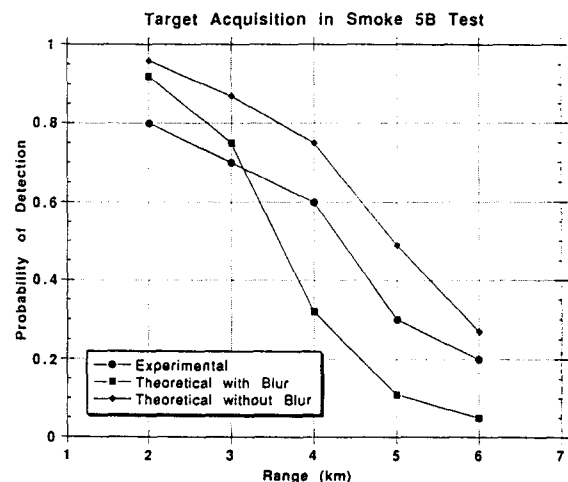


Fig. 6. Probability of detection at sixty seconds versus range for AN/TAS-4 Night Sight Sensor. Other parameters taken from Tables 4–6.

Table 4
Characteristic of target

s	3
ϵ	2
ΔT	2°C
R	Values between 2 and 5 km
β_{atm}	0.15 km ⁻¹
CF	2

Table 5
Characteristic of sensor

MRT ₀	0.03°C
β_{sys}	0.7 mrad/cycles

Table 6
Characteristics of search process

γ	1-detection
Field-of-view	6.8°
v	0.04 rad/sec
type of search	windshield wiper
t_i	0.01 sec
N	9

2 km and the angular velocity is allowed to vary from 0.01 to 0.11 rad/sec. As can be seen, a definite maximum occurs where the ability to get to the target quickly maximally outweighs the blur caused by the sensor motion. Indeed, many observers had slew rates close to this maximum.

7. Conclusions

We have constructed a model for human target acquisition which includes both the blurring effect of the sensor motion and the difference in individual search pattern. We find that a typewriter search is optimum with a sensor slew rate dependent on the sensor and target characteristics. The actual implementation of this model has been considered; several standard cases of search with actual military equipment have been considered and analyzed. The results of the smoke 5B Field Test of the U.S. Army has been analyzed with this model.

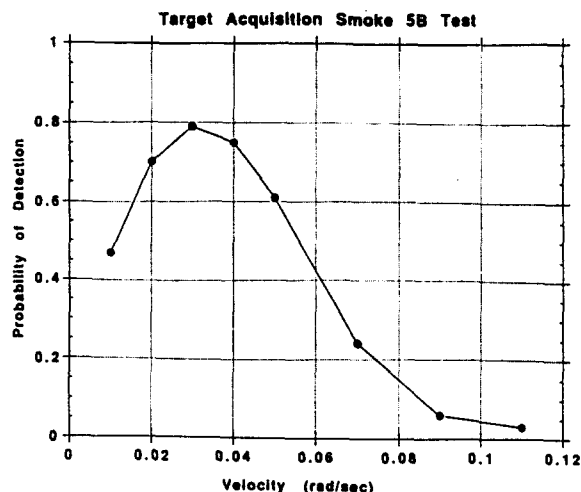


Fig. 7. Probability of detection at sixty seconds versus slew rate for AN/TAS-4 Night Sight Sensor at 2 km Range. Other parameters taken from Tables 4–6.

Acknowledgments

This research is partially supported by the Paul Ivanier Center for Robotics and Production Management, Beer-Sheva, Israel.

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